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Abstract

The successful commissioning and operation of the PEP-II asymmetric e^+e^- collider motivated further studies to increase luminosity. In this paper, we discuss a modification of the PEP-II lattice to reduce the vertical beta function at the Interaction Point (IP) from the design value of $\beta_y^* = 1.5cm$ to $1.0cm$. This could potentially reduce the colliding beam size, increase the particle density at IP and the probability of beam-beam interactions. In this paper, we outline the optics modifications, discuss tracking simulations, and overview machine implementation.

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UPGRADE OF THE PEP-II LOW BETA OPTICS†

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Abstract

The successful commissioning and operation of the PEP-II asymmetric e^+e^- collider motivated further studies to increase luminosity. In this paper, we discuss a modification of the PEP-II lattice to reduce the vertical beta function at the Interaction Point (IP) from the design value of $\beta_y^* = 1.5cm$ to $1.0cm$. This could potentially reduce the colliding beam size, increase the particle density at IP and the probability of beam-beam interactions. In this paper, we outline the optics modifications, discuss tracking simulations, and overview machine implementation.

1 INTRODUCTION

The luminosity of the PEP-II asymmetric e^+e^- collider [1] has been steadily increased since the beams were first brought into collision in July 1998. The present record luminosity is $2.2 \cdot 10^{33} cm^{-2}s^{-1}$ which is 73% of the design value. The luminosity is currently limited by the total beam current which is below design value due to vacuum chamber heating problems near IP in the High Energy Ring (HER) and electron cloud instability in the Low Energy Ring (LER). While it may take some time before all design beam parameters are achieved, other options can be explored to increase the luminosity. Specifically, the vertical β_y^* function at the IP could be reduced below its design and operating value of $1.5cm$. With preserved beam emittance, this would result in a smaller colliding beam size, increased probability of particle interactions and, hence, the luminosity. In this paper, we discuss an upgrade of the PEP-II Interaction Region (IR) [2] to reduce the β_y^* to $1cm$. The potential improvement of the luminosity is up to 22.5% if the emittance and other beam parameters are not changed, and up to 50% if vertical emittance is reduced with the same rate as β_y^*. One limitation on the minimum β_y^* is placed by the bunch length which is currently about $\sigma_l \approx 1cm$. Reduction of β_y^* below this level would not be very effective because the colliding area at the bunch ends ($\pm\sigma_l$ from IP) will start to grow and offset the luminosity gain near the bunch center.

2 BETA SQUEEZE

The PEP-II has been operated for more than a year with the design values of $\beta_x^*/\beta_y^* = 50/1.5cm$. In order to raise the luminosity, our present goal is to reduce β_y^* to $1cm$, the level of the bunch length. The Interaction Region has locally matched optics and local correction systems [2]. One of the requirements for the IR with lower β_y^* is to maintain locally matched optics and correction systems to avoid global optics perturbations. This requires simultaneous adjustment of the following IR magnets: 1) quadrupoles; 2) local sextupoles compensating non-linear chromaticity from the final focus doublets; 3) local skew quadrupoles compensating x-y coupling caused by the detector solenoid; and 4) local dipole correctors compensating orbit from the tilted solenoid.

The theoretically matched IR optics with $\beta_y^* = 1cm$ was developed for the HER and LER using MAD code [3]. The most noticeable and unavoidable effect caused by the lower β_y^* is an enlargement of β_y peak at the final focus doublets, proportional to $1/\beta_y^*$. The higher β_y peak further increases sensitivity of the doublets to field, alignment and energy errors. At $\beta_y^* = 1cm$, the natural vertical chromaticity grows by 24% and 15% in the HER and LER, respectively, mainly due to increased contribution from the doublets. Compensation of doublet chromaticity was done mostly by raising the field in the vertically correcting IR sextupoles by 37% in HER and 22% in LER. In the LER, the desired field at these sextupoles (SCY3) could not be reached due to magnet field limitation, hence the β_y function at the SCY3 was raised by 11% to compensate the lack of the field. The strengths of the IR local skew quadrupoles were adjusted to account for the change in optical transformation between the solenoid and the skew quads.

Because of independent optics adjustment on the left and right side of IR, about 40 magnet families in each ring change strength to make $1cm$ lattice. The typical quadrupole field change is a few percent, but several quads require 10-18% change. As stated earlier, the sextupoles correcting the doublets require the most raise in magnet field. The strength change of IR skew quadrupoles have rather large variation, though many of the quads have reduced field. At $\beta_y^* = 1cm$, the new IR strengths are still within magnet limitations except the LER SCY3 sextupoles described above and LER SK5 and SK5L skew quadrupoles. In the latter case the required skew quadrupole strength was made up by creating $\sim 2mm$ vertical orbit bumps in the SCY3 sextupoles located next to SK5 and SK5L. The B1 and QD1 magnets near IP, shared by the two beams, were not changed, therefore each ring could be adjusted independently.

Machine implementation and tuning of the more sensitive $1cm$ optics could be difficult without smooth transition from the present IR configuration. For that reason, an intermediate matched optics with $\beta_y^* = 1.25cm$ was designed. Furthermore, a two step linear "low beta knob" was made to provide a continuous transition from $\beta_y^* = 1.5cm$ to $1.25cm$ (step 1) and from $1.25cm$ to $1cm$ (step 2). In each step, all IR variable strengths are linearly changed with β_y^*

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between two matched configurations. With this knob, the IR optics would not be exactly matched everywhere except the above three β_y^* points. However, the residual optics effects for entire transition are rather small. MAD calculations show that distortions are below 0.0007 for betatron tune, 0.2 for chromaticity and $\pm 3\%$ for β functions. Therefore potentially, the knob could be used not only for transition, but for operation at transition β_y^* as well.

3 TRACKING SIMULATIONS

At lower β_y^*, the higher sensitivity of IR doublets to errors and stronger sextupoles could increase the effects of betatron resonances and lead to reduced dynamic aperture, especially in the vertical plane where most optics changes have occurred. To evaluate the impact of the new optics on dynamic aperture, we performed tracking simulations at the present and lower β_y^* values, using LEGO code [4]. To identify the nearby resonances which may be affecting the beam lifetime, dynamic aperture was also scanned around machine working point.

3.1 Dynamic Aperture

The typical tracking simulation with LEGO included: 1) an assignment of field, multipole and alignment errors to magnets according to PEP-II specifications; 2) global correction of tune, linear chromaticity, coupling and orbit; and 3) tracking of particles injected at various x and y amplitudes to determine dynamic aperture, the area of particle stable motion. The particles were tracked for 1024 turns with synchrotron oscillations and initial relative energy error of $8\sigma_\delta$, where σ_δ is 0.061% in HER and 0.077% in LER. The tracking was done at the present machine tune of ν_x/ν_y = 24.569/23.639 in HER and 38.649/36.564 in LER, and the dynamic aperture was evaluated at the PEP-II injection point. The typical rms orbit observed in the PEP-II operation is on the order of $1mm$. For realistic results, the orbit correction in the simulations was adjusted to provide similar residual orbit. The linear chromaticity was corrected to zero for the tracking. The beam-beam effects were not included at this time.

The tracking results at $\beta_y^* = 1.5cm$, $1.25cm$ and $1cm$ for both rings are shown in Fig. 1, where the dash lines correspond to dynamic aperture at injection point for 10 different machine error settings, and the solid ellipse shows for comparison the size of $10\sigma_{x,y}$ fully coupled beam with emittance of $\epsilon_x = 48nm$ and $\epsilon_y = \epsilon_x/2$. Note that normally the circulating beam with corrected coupling has ϵ_y/ϵ_x ratio on the order of 3% and the $10\sigma_y$ size four times smaller compared to the ellipse in Fig. 1. However, it is important to maintain large vertical dynamic aperture because of the vertical injection with initial amplitude equal to $\sim 8\sigma_y$ of a fully coupled beam. The x-offset of the LER dynamic aperture in Fig. 1 is due to non-zero dispersion at the LER injection point and $8\sigma_\delta$ initial energy error in tracking.

As shown in Fig. 1, the lower β_y^* causes gradual reduction of dynamic aperture. Compared to $1.5cm$ lattice, dynamic aperture at $1cm$ is reduced by about 15% and 30% in the x and y planes, respectively. The vertical aperture is more affected since most optics changes occurred in the vertical plane. For instance, at lower β_y^*, particles in the vertical plane experience stronger non-linear field in the IR doublets and IR vertically correcting sextupoles due to larger oscillations in the doublets and stronger sextupoles.

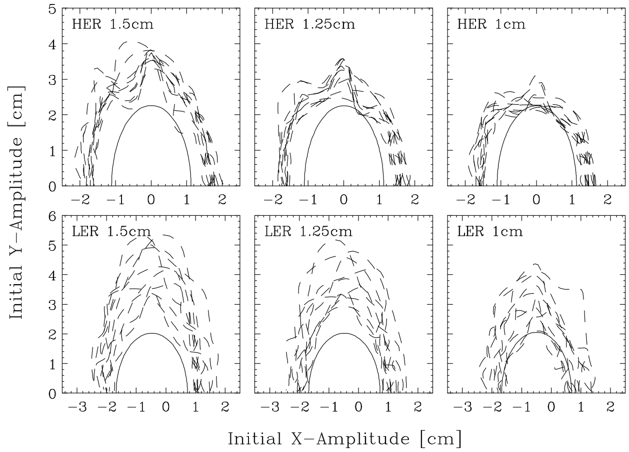

Figure 1: Dynamic aperture vs. β_y^* for 10 error settings.

According to Fig. 1, it is expected that operation at lower β_y^* would require more careful machine tuning to minimize any effects causing large particle oscillations. It appears that injection conditions are adequate at $1.25cm$, but become tighter at $1cm$. Note that dynamic aperture in Fig. 1 is for particles in the tail of energy distribution ($\delta = 8\sigma_\delta$). The particles in the beam core will have larger aperture.

3.2 Tune Scan

The working point used in the current PEP-II operation and in this study differs from the design [1]. It was selected experimentally in the machine operation based on maximum luminosity, while the design tune was better optimized for maximum dynamic aperture with single beam. For better understanding the tune space and effects of betatron resonances near present working point, dynamic aperture tune scan was performed. In this study, the betatron tune was varied in 0.0025 steps around the machine working point within the range of ± 0.04 for ν_x and ν_y, and dynamic aperture was calculated at each point. Due to extensive computing time in this study, the number of particle launching conditions was limited to five, namely with 1-2) $\pm x$, $y = 0$; 3) $x = 0$, $y > 0$; and 4-5) $x = \pm y$, $y > 0$ initial amplitudes. The minimum aperture among the five conditions at each tune point was then used to determine dynamic aperture dependence on ν_x and ν_y. As in the previous study, machine errors were applied to the magnets, and the initial particle energy error was set to $8\sigma_\delta$ with synchrotron oscillations included. Similar to machine operations, the tune variation was done with the "tune knob" which uses pre-calculated linear dependence of quadrupole strengths in the tune sections with the tune.

The HER and LER tune scan diagrams for $\beta_y^* = 1cm$

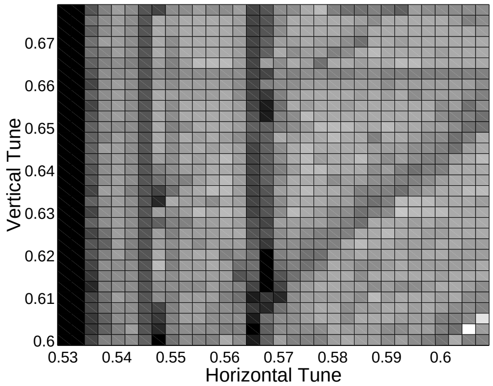

Figure 2: HER tune scan for $\beta_y^* = 1cm$.

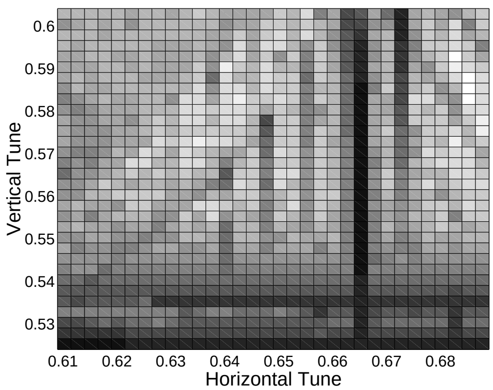

Figure 3: LER tune scan for $\beta_y^* = 1cm$.

are shown in Fig. 2 and 3, where a smaller aperture corresponds to a darker shade and the present working point is in the center. Numerical analysis of the tune scan reveals several lines of reduced dynamic aperture on the tune plane, associated with synchro-betatron resonances.

In the HER, the strongest resonance identified near working point is $2\nu_x + k\nu_s = 49$, where $k =$ -1,-2,-3 and the synchrotron tune $\nu_s = 0.044$. The dynamic aperture practically disappears at the first synchrotron side band of the $2\nu_x$ resonance. Two other weaker resonances were observed: $3\nu_y = 71$ and $\nu_x - \nu_y + \nu_s = 1$. According to the tune scan, the HER aperture could be improved by moving further away from the nearby $2\nu_x - 3\nu_s$ resonance.

In the LER, the following resonances were identified: 1) $2\nu_y + l\nu_s = 73$, with $l =$ -2,-3; 2) $3\nu_x + m\nu_s = 116$, with $m =$ -2,-1,0,1; and 3) $2\nu_x + \nu_y + n\nu_s = 114$, with $n = 1,2,3$ and $\nu_s = 0.025$. The first two resonances above are the strongest and result in rather small or vanished dynamic aperture close to resonance conditions. The effect is more pronounced near the lowest order synchrotron side bands of the resonances. Compared to $1.5cm$ lattice, at $\beta_y^* = 1cm$ the $2\nu_y + l\nu_s$ resonance is enhanced due to increased vertical chromaticity and sensitivity in the IR doublets, thus further limiting the available vertical tune space near the working point. According to the tune scan, the LER dynamic aperture could be improved by increasing the ν_y and reducing the ν_x tunes by ~ 0.015, however the beam-beam conditions in this area have not been verified yet.

Note that the tune scan results are valid for one particular set of machine errors and particles with $\delta = 8\sigma_\delta$ oscillations. Particles with smaller energy error will be less affected by the resonance synchrotron side bands.

4 MACHINE IMPLEMENTATION

The first step of the described low beta modification has been recently implemented in the machine, and the IR optics is currently set at $\beta_y^* = 1.25cm$. The transition to $1.25cm$ lattice was done using the "low beta multi-knob" described earlier, with the beams stored in the machine. In this way, any residual distortions (tune shifts, chromaticity, etc.) could be compensated as they appeared in the transition, and any effect of the larger beam size in the IR quadrupoles on the backgrounds could be detected immediately. The spurious tune shift observed during this operation was about 0.006 in x and < 0.001 in y planes. The global change in the beam orbit was $\sim 0.4mm$, which was easily compensated with orbit correctors. Residual chromaticity amounted to less than one unit in either plane.

The effect of the new β_y^* on lattice functions was verified using the on-line phase advance and β function measurement facility. Fig. 4 shows the ratio of the new HER β_y functions with respect to the old values, measured at BPMs (circles) near IP (at center of the figure). The agreement with the MAD prediction (solid line) is satisfactory.

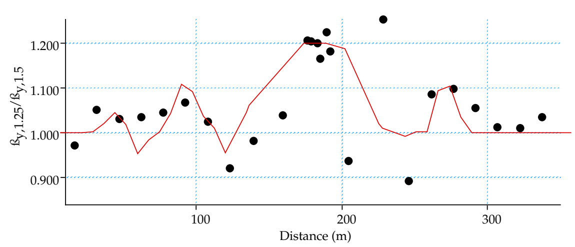

Figure 4: Ratio of HER β_y functions near IP at $\beta_y^* = 1.25cm$ with respect to β_y values at $\beta_y^* = 1.5cm$.

No increase in the background was observed during and after implementing the $1.25cm$ lattice. Luminosity did not visibly increase immediately after the β_y^* change. A few days later, solenoids to reduce the effect of photoelectrons on the LER beam were powered up. After that, luminosity increased significantly, raising the record from the previous value of $1.6 \cdot 10^{33}$ to $1.95 \cdot 10^{33} cm^{-2}s^{-1}$.

5 REFERENCES

[1] PEP-II Conceptual Design Report, SLAC–418, 1993.

[2] Y. Nosochkov *et al.*, "Lattice and Compensation Schemes for the PEP-II Interaction Region", ICFA'97, Frascati, 1997.

[3] H. Grote, F. C. Iselin, CERN/SL/90–13 (AP) Rev.4, 1994.

[4] Y. Cai, *et al.*, SLAC–PUB–7642, 1997.